

# EMISSION CONTROL TECHNOLOGIES FOR OCEAN GOING VESSELS (OGVs)

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# Acknowledgement

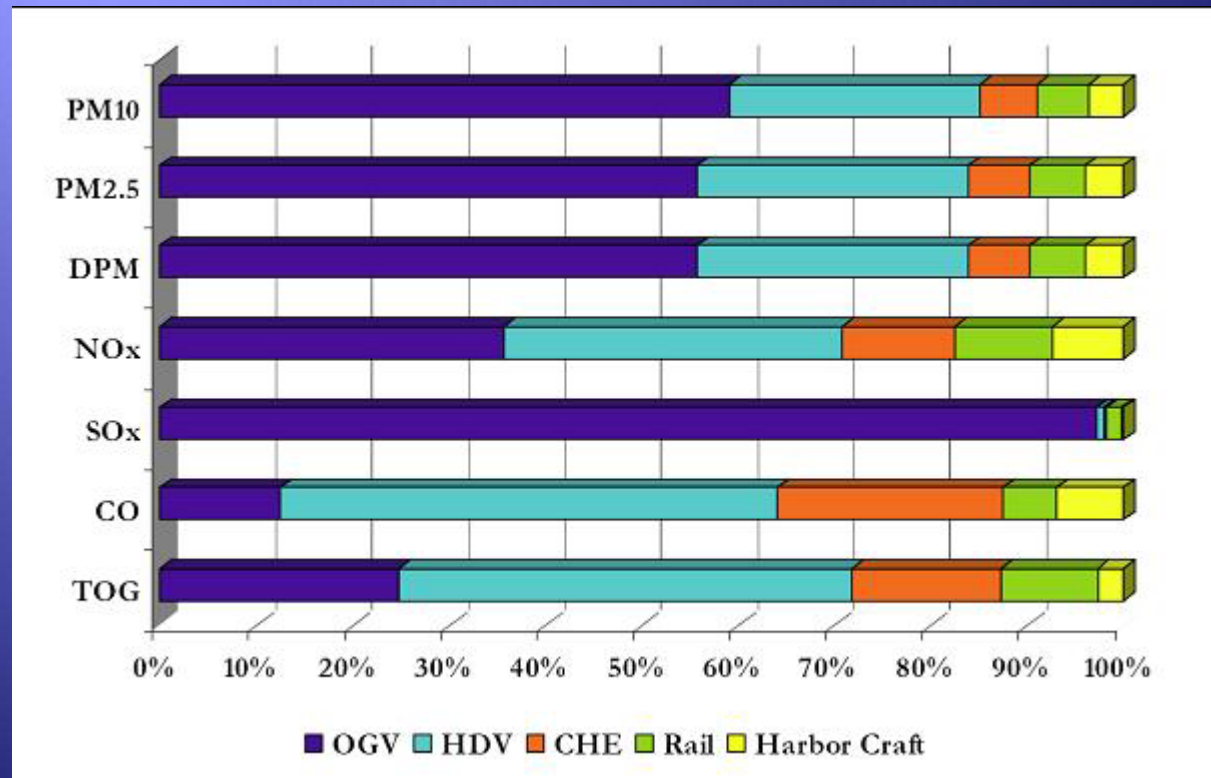
We would like to thank Mr. Steve Church and Mr. Paul Milkey from CARB for their extensive and valuable guidance during the course of this study.

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# Objectives:

- ◆ A comprehensive survey of existing, developing, and planned technologies that are used or could be adapted and reasonably be used to control NO<sub>x</sub>, SO<sub>x</sub>, and PM emissions from the diesel cycle propulsion and auxiliary engines of OGVs,
- ◆ Collect and assess available performance data for these technologies, and evaluate these technologies for meeting target emissions and for their initial, installation and operating costs and their adaptability for the current and new OGVs.

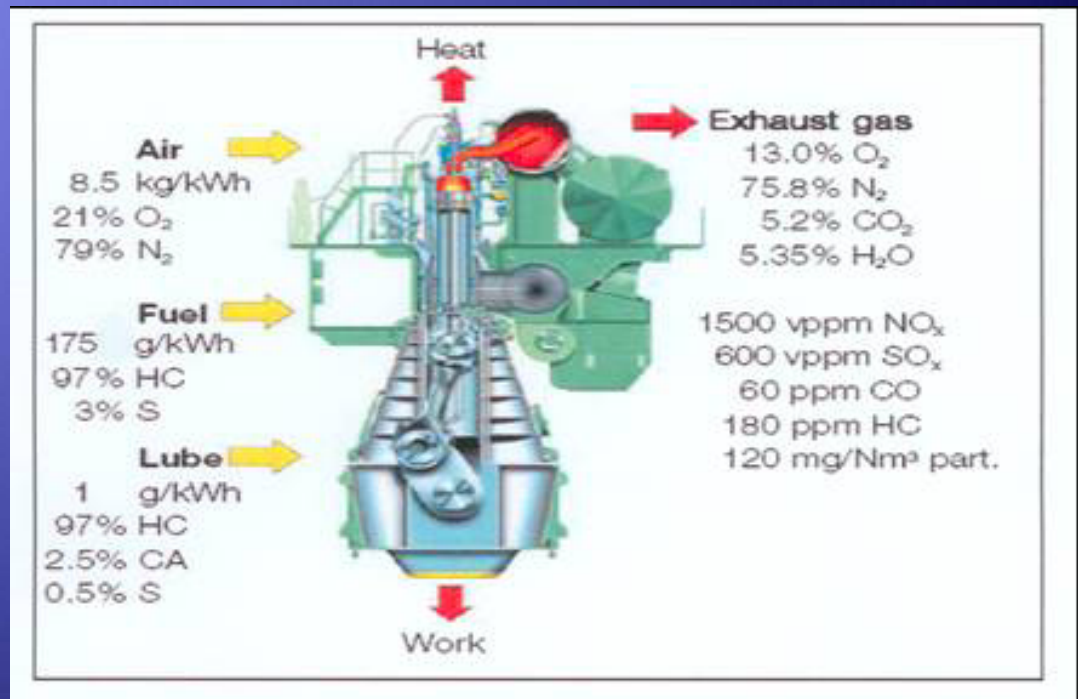
# 2005 Port of Los Angeles Inventory of Air Emissions



# Engines and Emissions

- Main Engine: Two-stroke reciprocating diesel engine, low rpm (60-250), directly connected to the propeller, high efficiency (48%-54%), used in ships with a tonnage at or higher than 5000.
- Four-stroke diesel engines: Used in ships with tonnage less than 5,000, connected to the ship's propeller, through gear boxes, higher rpm (can reach 1000), on the average 3-4 engines are used. Can also be used as auxiliary engine.

## Intake and Exhaust of a Ship Engine (Man B & W, 2004)



# A Two-Stroke Marine Engine





# Emissions of Diesel Engine and Gas Engine

- Common fuel for OGVs is heavy fuel oil (HFO). On the average it has 2.7% sulfur, which is a source of PM.
- Carbon monoxide from marine diesel engines are significantly lower than those for the gas engines due to their high efficiency while the reverse is true for nitrogen oxides.
- High temperature combustion in diesel engines contributes significantly to the NO<sub>x</sub> formation.

Component	Diesel Engine	Gas Engine
Nitrogen oxides, NO <sub>x</sub>	700 – 1.500 ppm (v/v)	60 – 130 ppm (v/v)
Sulfur oxides, SO <sub>x</sub>	30 – 1.000 ppm (v/v)	0 – 3 ppm (v/v)
Carbon monoxide, CO	20 – 150 ppm (v/v)	200 – 500 ppm (v/v)
Hydrocarbons THC	15 – 100 ppm (v/v)	1.000 – 2.200 ppm (v/v)
Particulate matter PM	20 – 100 mg/ nm <sup>3</sup>	

ppm (v/v): parts per million by volume.

mg/ nm<sup>3</sup> : milligrams per nominal cubic meter (temperature = 0° C and pressure = 101.3 kPa).

# Cost Effectiveness

Cost (\$)/Ton of pollutant removed.

$$\frac{\text{Annual Cost of Any Measure}}{\text{Annual Emission Reduction of that Measure}}$$

Annual cost include capital costs distributed over the life span of the equipment, and ongoing operation and maintenance costs.



# Methods and Technologies for Reducing Emissions from Marine Diesel Engines

- ◆ **Engine Optimization**

Involves control of “in cylinder” parameters for reducing engine emissions and improving fuel economy.

- ◆ **Engine Process Modifications**

Modifications and control of combustion processes.

- ◆ **After Treatment processes**

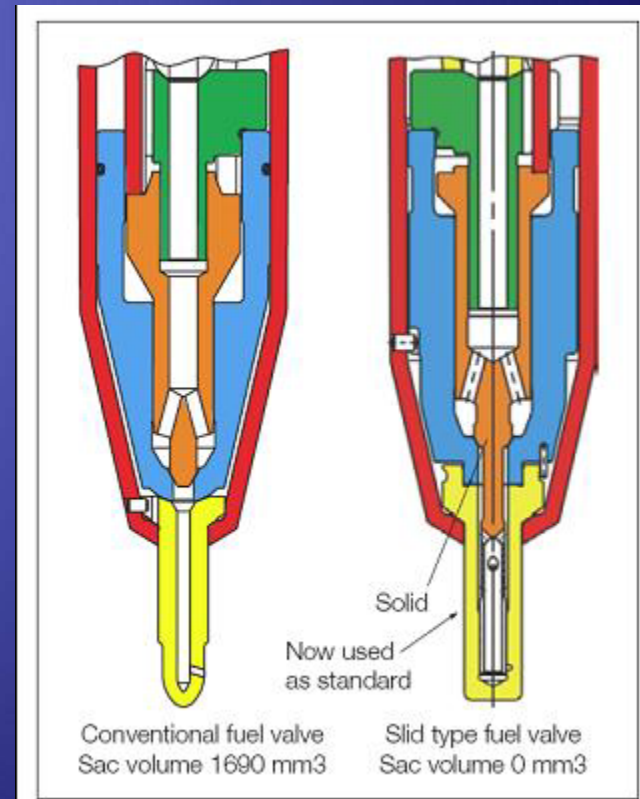
Treatment of exhaust gases

# Engine Optimization Process (EOP)

- ◆ Optimization of combustion chamber geometry
- ◆ Optimization of combustion residence time
- ◆ Control of lubrication process
- ◆ Common rail system
- ◆ Increased compression ratio
- ◆ Improving injection nozzle geometry
- ◆ Control of fuel injection process
- ◆ Miller cycle valve timing

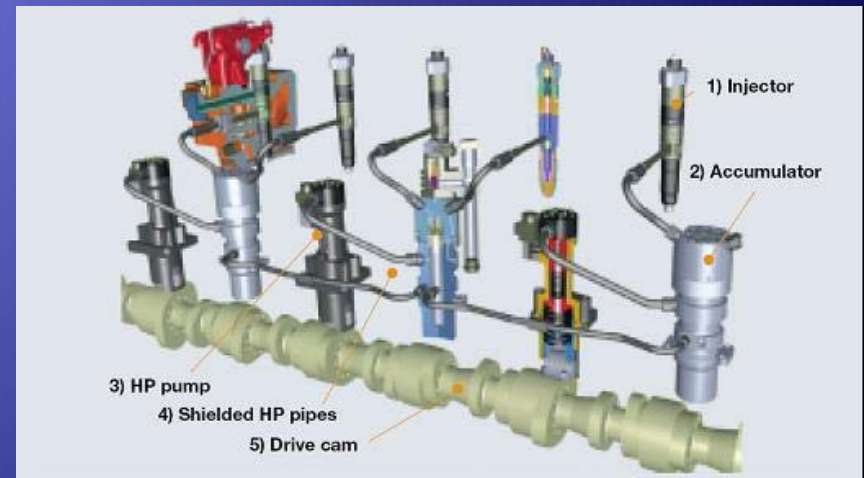
# EOP (Slide valves)

- ◆ Slide valves are used for optimizing spray distribution in the combustion chamber, while the engine temperature is kept constant.



# EOP (Common Rail)

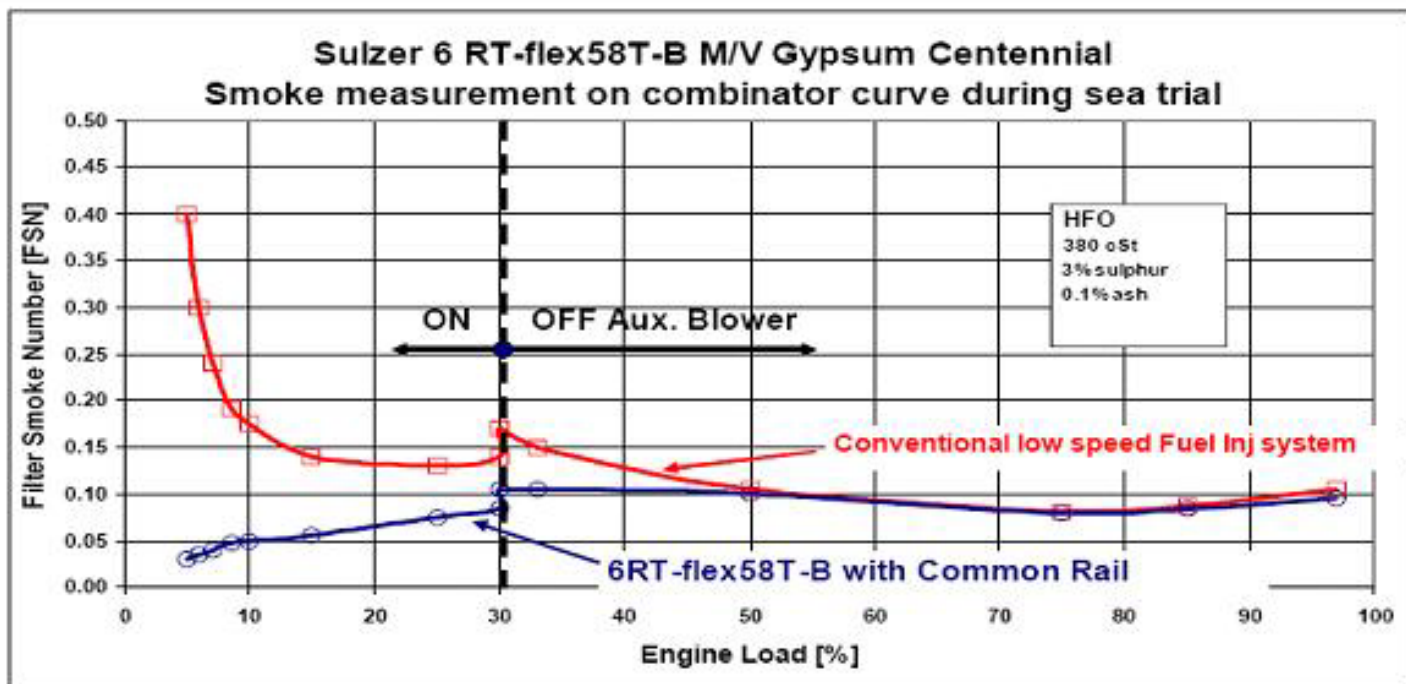
- ◆ It allows individual control of injection timing and duration for optimized injection at different loading conditions.
- ◆ It eliminates visible smoke from the exhaust, especially at low engine loads.



# EOP (Miller Cycle-4-Stroke)

- ◆ Lower compression ratio (obtained by early or late inlet valve closing or by opening the exhaust valve during compression)
- ◆ High pressure turbo-charging
- ◆ Variable air inlet valve timing
- ◆ Charged-air cooling
- ◆ Field test showed 35% reduction in NO<sub>x</sub>
- ◆ Results in increased PM emission, because less soot is oxidized at lower temperature. It also results in increase fuel consumption by about 1%.

# EOP (Common Rail)



# Engine Process Modifications (EPM)

- ◆ Addition of water, urea, or ammonia to the combustion process.
- ◆ Electronic control of fuel injection and exhaust gas valve for meeting optimum emission reduction at all loads.
- ◆ Exhaust gas recirculation with low sulfur fuel or in combination with the scrubbing system for reducing NO<sub>x</sub> emissions.



# Water Injection for NOx Reduction

## ◆ Direct High Pressure Water Injection

The water-to-fuel injection weight ratio is 0.4-0.7. It has the potential to reduce NOx by 50-60% (Wartsila, 2006). Effective NOx reduction is obtained for engine load higher than 40%.

## ◆ Emulsified Fuel

Mixing water and diesel fuel. Optimum NOx reduction capability is 20-20%. There are two approaches for adding water:

- Un-stabilized Emulsion
- Stabilized Emulsion

## ◆ Fumigation

Adding humidity to the intake air. Humidity-fuel ratio is about 3:1. It can achieve 70%-80% NOx reduction. It requires distilled water. High initial investment cost.

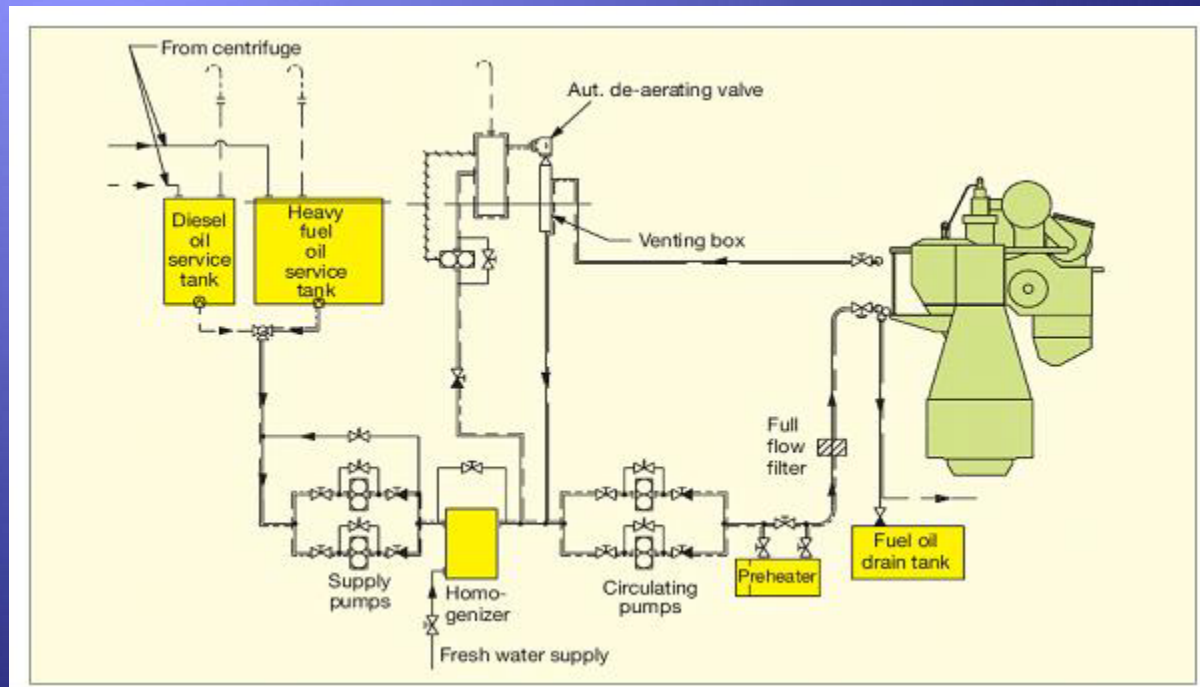
# Cost Effectiveness of Direct Water Injection

Measure	Ship type	Emission	Small Vessel	Medium Vessel	Large Vessel
			\$/ ton	\$/ ton	\$/ ton
Direct water injection	New	NOx	\$371.31	\$325.23	\$311.68

# Cost Effectiveness of Adding Humidity to the Intake Air

Measure	Ship type	Emission	Small Vessel	Medium Vessel	Large Vessel
			\$/ ton	\$/ ton	\$/ ton
Humid air motors	New	NOx	\$242.12	\$207.79	\$178.88
Humid air motors	Retrofit	NOx	\$276.45	\$254.77	\$237.60

# Un-Stabilized Emulsion



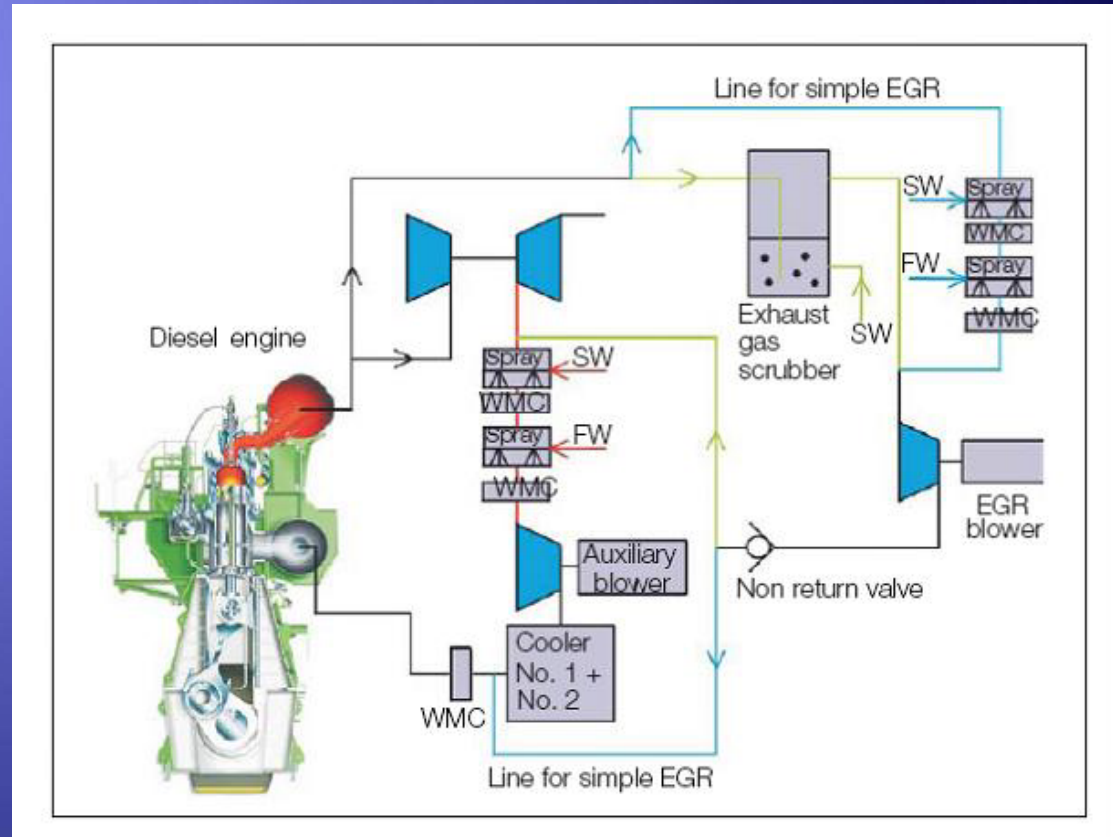
# Exhaust Gas Recirculation

- Input compressed air is mixed with a portion of pre-cooled filtered exhaust gas, decreasing oxygen content of the intake air resulting in reduced NO<sub>x</sub> production.

- At 75% load, with 20% recirculation, 50% NO<sub>x</sub>, 20% PM, and 10% HC reductions are achieved. But Co is increased by 200% and there was a slight increase in fuel consumption.

- Not appropriate when residual fuel is used due to high sulfur content.

EGR and Scrubbing system for a 4-stroke Marine Diesel Engine (Man B&W, 2004)



# Selective Non-Catalytic Reduction (SNCR) For NO<sub>x</sub> Reduction

- ◆ Injection of Urea or Ammonia into the combustion chamber or in the exhaust gas, immediately after the combustion chamber. It does not need a catalyst.
- ◆ Require a temperature range of 900°-1000° C to be effective. Above 1000° NO<sub>x</sub> production is increased and below 900°C, there will be ammonia slippage.
- ◆ Has the potential to reduce NO<sub>x</sub> by more than 95%.
- ◆ Requires large amount of ammonia or Urea.

# After Treatment Processes (ATP)

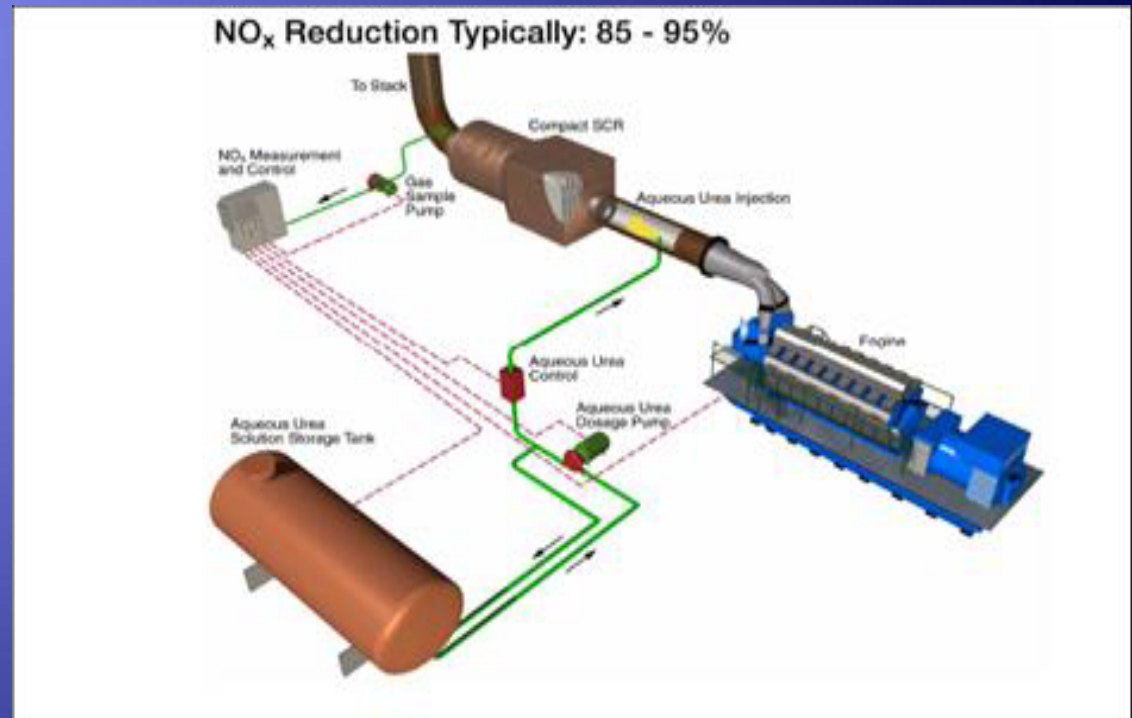
- ◆ Selective Catalytic Reduction (SCR) system for reducing NO<sub>x</sub>.
- ◆ Seawater scrubbing system for reducing PM emissions.
- ◆ Diesel Particulate Filter (DPF) for reducing PM emission in auxiliary engine using low sulfur fuel.
- ◆ Lean NO<sub>x</sub> Trap (LNT), NO<sub>x</sub> Absorber Catalyst (NAC)



# SCR System for NOx Reduction

- Appropriate when low sulfur fuel is used. For high sulfur fuel, SOx in exhaust oxidizes to form sulfuric acid and also high level of SOx reduces the capacity of the catalyst to absorb NOx.
- Works well when exhaust temperature is between 290-350 C.
- Has the potential to remove NOx by more than 90%. It also reduces HC and CO emissions.
- Requires an extra tank of aquatic urea or ammonia. Generally 40% urea-water mixture is used.

## SCR System for a 4-Stroke Marine Engine



# Cost Effectiveness of SCR Systems

Measure	Ship type	Emission	Small Vessel	Medium Vessel	Large Vessel
			\$/ ton	\$/ ton	\$/ ton
SCR outside SO <sub>2</sub> ECA	New	NO <sub>x</sub>	\$668.53	\$508.63	\$475.20
SCR outside SO <sub>2</sub> ECA	Retrofit	NO <sub>x</sub>	\$730.87	\$552.90	\$515.86
SCR inside SO <sub>2</sub> ECA	New	NO <sub>x</sub>	\$490.56	\$383.05	\$359.56
SCR inside SO <sub>2</sub> ECA	Retrofit	NO <sub>x</sub>	\$553.80	\$427.32	\$400.22
SCR, Ships using MD	New	NO <sub>x</sub>	\$373.11	\$299.94	\$282.77
SCR, Ships using MD	Retrofit	NO <sub>x</sub>	\$436.35	\$344.20	\$323.43

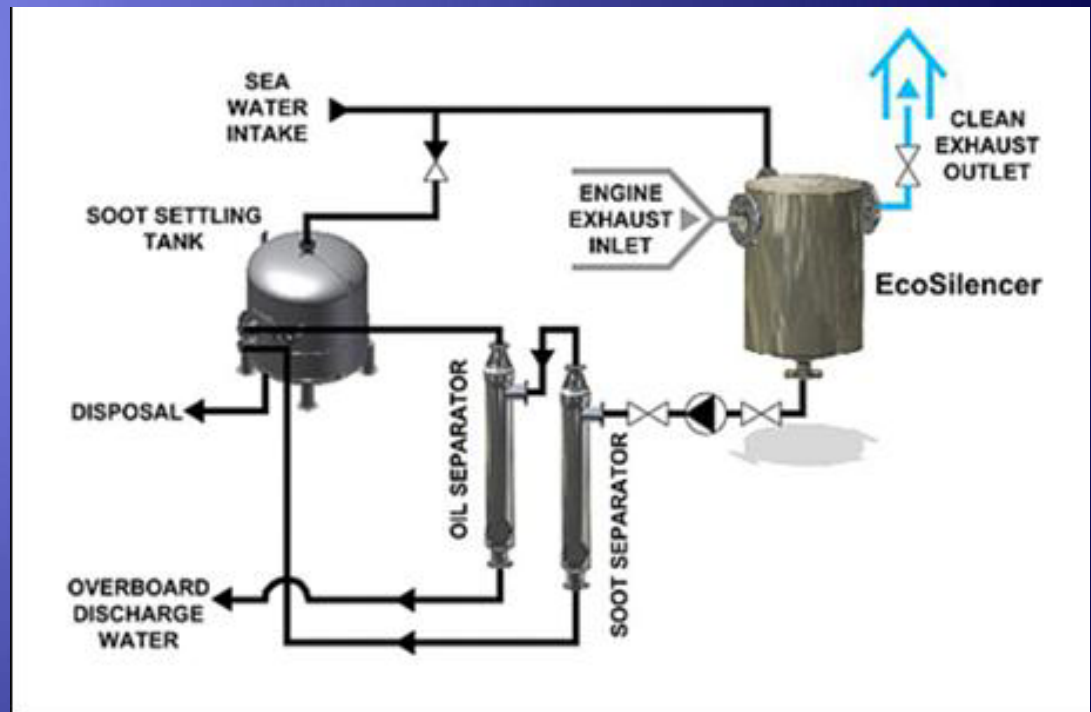
# Seawater Scrubbing System

Average SO<sub>x</sub> removal is 75-80 percent and PM removal is 25-30 percent.

There is a possibility of sulfuric acid vapor formation from reaction SO<sub>3</sub> with exhaust mist. To avoid local plume grounding and acid contamination, exhaust gas is reheated to increase the temperature by 20-30 degrees to eliminate steam plume.

Major concern is the quality of discharged water, even with water treatment facility.

A Scrubbing System with Soot Removal and Water Treatment Unit.



# Cost Effectiveness of a Seawater Scrubbing System

Measure	New/ Retrofit	Emission	Small Vessel	Medium Vessel	Large Vessel
			\$/ ton	\$/ ton	\$/ ton
Sea water scrubbing	New	SO <sub>2</sub>	\$352.34	\$317.10	\$289.10
Sea water scrubbing	Retrofit	SO <sub>2</sub>	\$520.37	\$483.33	\$455.33

# Oxidation Reactors

- It converts CO and HC to CO<sub>2</sub> and H<sub>2</sub>O and also remove the portion of PM associated with soluble organic compounds.
- It can place upstream of the SCR system for removal of CO, HC, and NO<sub>x</sub>.
- High sulfur fuel reduces the effectiveness of diesel oxidation catalyst and results in production of sulfate particles.



# NOx Absorber Catalysts

- ◆ The NOx absorber catalysts (NAC) use “base metal oxide” and precious metal coating to absorb NOx during engine lean operating conditions. When the maximum NOx storage condition is met, the catalyst goes through a regeneration process to release the NOx absorbed.
- ◆ Sulfur in fuel oil poses challenges to the NAC and makes it ineffective and thus the NAC has not been a viable option for reducing NOx emissions of OGVs.

# Lean NOx Trap (LNT)

- ◆ Lean NOx catalysts have similar design characteristics as NOx absorber catalysts but without the regeneration process. Their successful operation depends on continuous injection of hydrocarbon upstream of the catalyst for converting absorbed NOx to nitrogen.

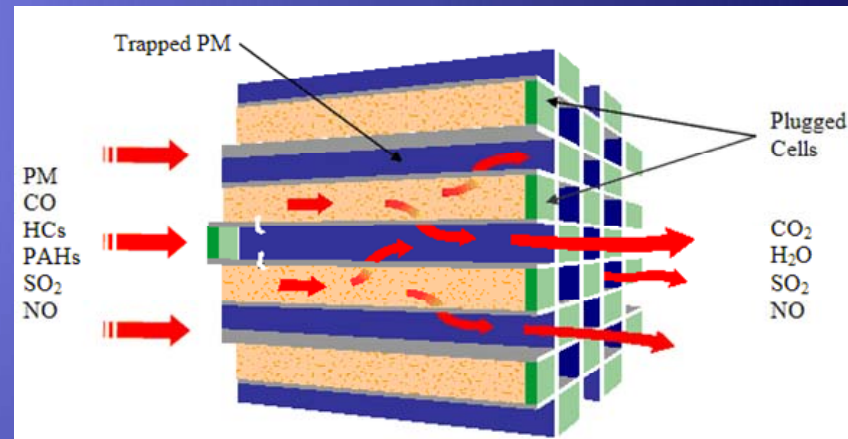


# Diesel particulate Filter (DPF)

It has two chambers.  
First it converts NO to NO<sub>2</sub> and then NO<sub>2</sub> reacts with particulate, converting them to CO, CO<sub>2</sub>, and inorganic dusts.

It is very sensitive to sulfur content of the exhaust gases. For high sulfur exhaust, there will be increased ash collection and thus increased maintenance cost. Requires regeneration process to remove the sulfur and maintain its effectiveness.

## Particulate Filter and Typical Muffler Construction



# Fuels and Alternatives

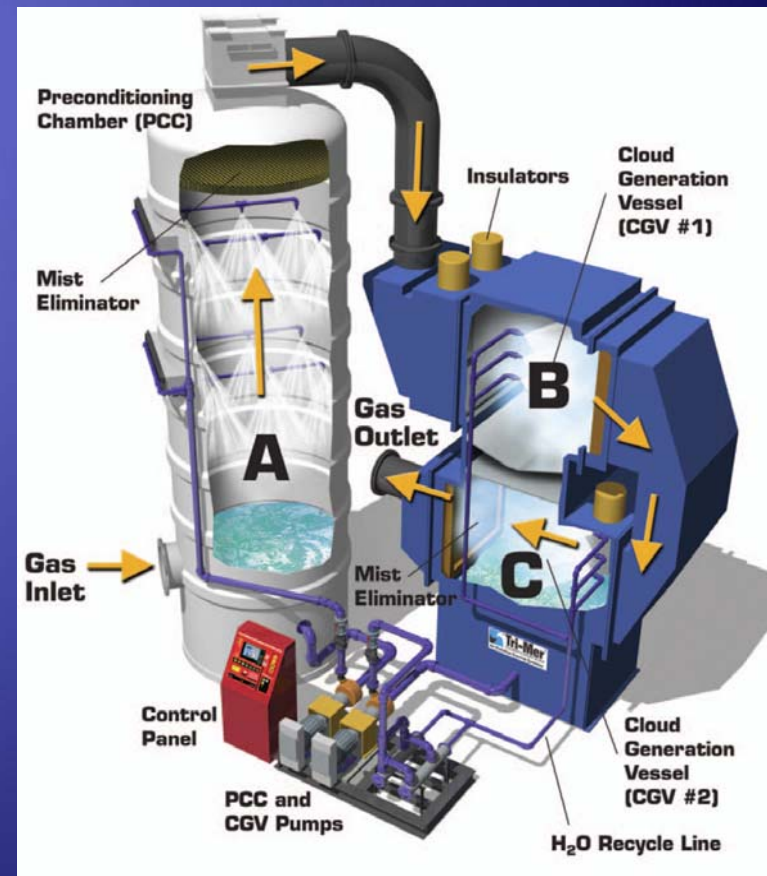
- ◆ Low Sulfur Diesel Fuel
- ◆ Dual-Fuel Marine Engine (natural gas mode/diesel mode)
- ◆ Biodiesel
- ◆ O2Diesel (ethanol-diesel fuel blend)
- ◆ Fuel Cell (Currently uses Hydrogen as the fuel)
- ◆ Gas Turbine
- ◆ Diesel Fuel with Hydrogen

# **Ships at Berth**

- ◆ Cold Ironing (Shore side Electricity): Running ship's auxiliary engine with shore side electricity. It is cost effective, when the cost of the health impact is taken into account.
- ◆ Cloud Chamber Scrubbing (SO<sub>x</sub> + PM) + SCR (NO<sub>x</sub>) system

# Cloud Chamber Scrubbing (Tri - Mer Corporation)

- ◆ Pre-conditioning chamber removes coarse particles and increase the size of sub-micron particles through saturation.
- ◆ Cloud Generation Vessel: Mixing and interaction between exhaust gas and mist
- ◆ Cooling of the exhaust stream.
- ◆ The system is claimed to remove more than 95% of SO<sub>x</sub> and PM on low sulfur fuel.



# Cloud Chamber Scrubber + SCR System

- ◆ A recent test by Advanced Cleanup Technologies, Inc. at the Port of Long Beach.
- ◆ Results are not available yet, but previous test on diesel locomotives with low sulfur fuel indicates 97% of NO<sub>x</sub> and SO<sub>x</sub> and 92% PM removal.

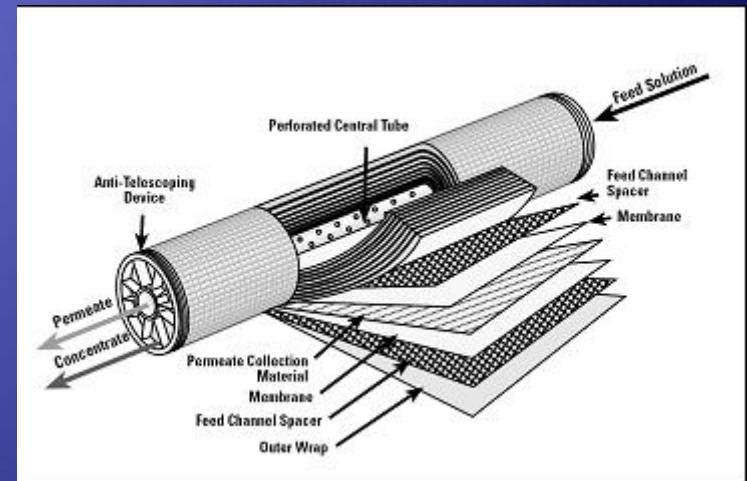




# Emerging Technology: Intelligent Energy (IE)

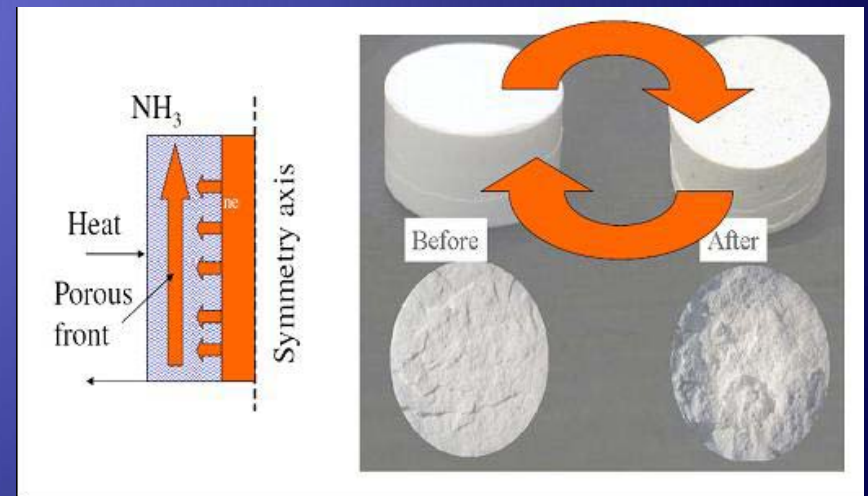
## Membrane-Based Fuel Sulfur Management System

- ◆ The main part of the system is a polymeric membrane. Two types are under development. Organic solvent nano filtration (OSN) and Pervaporation (permeation + evaporation) high flux membrane ( HFM).
- ◆ It can produce low sulfur fuel during ship's journey in the open seas and then use the fuel when operating at or near the port.



# Emerging Technology: Amminex A/S (of Denmark) Ammonia Storage and Delivery System.

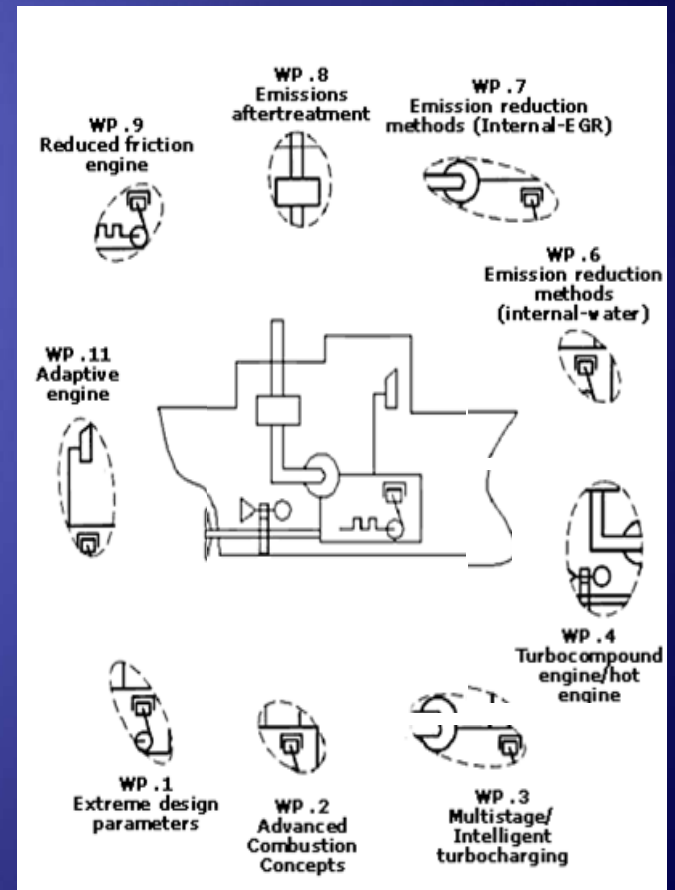
- ◆ It is called AdAmmine. It consists inorganic salt and Ammonia. It has the same capacity as liquid ammonia and more than three time the capacity of urea-based AdBlue.
- ◆ Long shelf life and low storage capacity. Requires low power to generate ammonia.





# IP-Hercules

I.P. HERCULES VISION	Year 2010	Year 2020
Reduction of fuel consumption and CO <sub>2</sub> emissions	-3%	-5%
Reduction of NO <sub>x</sub> (Relative to IMO 2000 standard)	-30%	-60%
Reduction of other emission components (PM, HC)	-20%	-40%
Improvement in engine reliability	+20%	+40%
Reduction of time to market	-15%	-25%
Reduction in lifecycle cost	-10%	-20%



# NOx Reduction of Different Measures as a Percentage of Baseline Emissions.

	NOx	sfc	SO <sub>2</sub>	VOC	PM
Basic IEM (Slide Valves)	-20%	*	*	*	*
Advanced IEM	-30%	*	*	*	*
Direct water injection	-50%	*	*	*	*
Humid Air Motor	-70%	*	*	*	*
Exhaust Gas Recirculation (ships using RO but Switching to MD (accounting for SO <sub>2</sub> & PM reductions))	-35%	0%	-93%	+/-	>-63%
Exhaust Gas Recirculation (ships originally using MD)	-35%	*	*	*	*
Selective Catalytic Reduction	-90%	*	*	*	*

# NOx Reductions in Tons per Year per Vessel

	Vessel		
	Small	Medium	Large
	(t NOx/ year)	(t NOx/ year)	(t NOx/ year)
Basic IEM (Slide Valves)	43	144	361
Advanced IEM	70	230	577
DWI	117	384	962
HAM	164	538	1346
EGR	82	269	673
SCR	211	691	1731

# SO<sub>2</sub> Reduction in Tons/Yr with Seawater Scrubbing

	Vessel		
Current	Small	Medium	Large
SO <sub>2</sub>	129	423	1056

# Cost Effectiveness of Different Measures for Removing NO<sub>x</sub>

Measure	Ship type	Emission	Small Vessel	Medium Vessel	Large Vessel
			\$/ ton	\$/ ton	\$/ ton
Basic IEM (2 stroke slow speed only)	New	NO <sub>x</sub>	\$10.84	\$8.13	\$8.13
Basic IEM (2 stroke slow speed only), young engines	Retrofit	NO <sub>x</sub>	\$10.84	\$8.13	\$8.13
Basic IEM (2 stroke slow speed only), older engines	Retrofit	NO <sub>x</sub>	\$54.21	\$21.68	\$13.55
Advanced IEM	New	NO <sub>x</sub>	\$88.54	\$29.81	\$17.17
Direct water injection	New	NO <sub>x</sub>	\$371.31	\$325.23	\$311.68
Humid air motors	New	NO <sub>x</sub>	\$242.12	\$207.79	\$178.88
Humid air motors	Retrofit	NO <sub>x</sub>	\$276.45	\$254.77	\$237.60
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# Cost Effectiveness for Seawater Scrubbing System and Fuel Switching

Measure	New/ Retrofit	Emission	Small Vessel	Medium Vessel	Large Vessel
			\$/ ton	\$/ ton	\$/ ton
Sea water scrubbing	New	SO <sub>2</sub>	\$352.34	\$317.10	\$289.10
Sea water scrubbing	Retrofit	SO <sub>2</sub>	\$520.37	\$483.33	\$455.33
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	SO <sub>2</sub>	\$1,854.73 (\$1,111.21)	\$1,852.02 (\$1,111.21)	\$1,847.50 (\$1,111.21)
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	SO <sub>2</sub>	\$1,854.73 (\$1,111.21)	\$1,852.02 (\$1,111.21)	\$1,847.50 (\$1,111.21)
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	SO <sub>2</sub>	\$1,300.03 (\$1,526.79)	\$1,299.12 (\$1,526.79)	\$1,295.51 (\$1,526.79)
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	SO <sub>2</sub>	\$1,300.03 (\$1,526.79)	\$1,299.12 (\$1,526.79)	\$1,295.51 (\$1,526.79)

# Observations

- ◆ Technologies such as particulate traps, oxidation catalysts, and exhaust gas recirculation (EGR) are not applicable for large heavy fuel operated diesel engines.
- ◆ Trap and catalyst are very sensitive to deactivation and EGR results in corrosion and contamination risks due to sulfur and ash in fuel.



# Observations.....

- ◆ For NO<sub>x</sub> reduction, SCR system is the most effective, but the costliest. The most balanced system is fumigation, followed by direct water injection.
- ◆ Due to the current cost of fuel switching, the most cost effective technology for reducing SO<sub>x</sub> and PM emissions is seawater scrubbing.